Approx. 580,000 bridges in the US (350,000 reinforced concrete and prestressed concrete bridges).

Approx. 15% structurally deficient bridges due to corrosion.

Annual direct cost $8.3 billion ($3.8 billion for bridge replacement and $2 billion for substructure maintenance).

Corrosion of reinforced concrete substructure
- Chloride-induced corrosion
- Splash zone/ tidal zone
- Concrete delamination/spalling
- Loss of concrete steel section

Corrosion causes reduced mechanical strength and increased costs.
Steel nominally develop passive film when embedded in concrete with alkaline pore water pH.

However, chlorides at sufficient concentrations causes depassivation.

High performance concrete and larger concrete cover delays chloride penetration.
CHLORIDE-INDUCED CORROSION

- Corrosion typically most severe in splash/tidal zones due to fast chloride penetration and oxygen availability.
- Corrosion service life described by initiation and propagations times.
  - Concrete Cover, X
  - Chloride Surface Concentration, Cs
  - Concrete Diffusivity, D
  - Chloride Threshold, $C_T$
  - Corrosion Rate

✓ Materials and design ideally would prevent corrosion initiation and prolong corrosion propagation.
CONVENTIONAL REPAIR OF R/C CONCRETE

• Conventional patch procedure
  • Removal of contaminated concrete
  • Rebar cleaning/replacement
  • Concrete restoration

• Patch repair failure often attributed to the Halo Effect.
• Other mitigation repair techniques can include concrete sealers, cathodic protection, inhibitors, etc…

• Repairs can be expensive and difficult to implement.

✓ Cost-effective repair methods with minimal maintenance and long-term durability of repaired substructure is needed.
• Initial steel passive condition due to formation of protective oxide film.
HALO EFFECT

- Introduction of chloride ions from the external environment.
HALO EFFECT

- Introduction of chloride ions from the external environment.
HALO EFFECT

- Chloride levels at rebar surface exceeds critical threshold concentration.
Corrosion initiation at anodes results in active potentials.
HALO EFFECT

- Extended cathodes support corrosion cell.
• Cathodic polarization of sites adjacent to local anode.
• Chloride levels adjacent to local anodes not insignificant.
And chloride levels increase in time.
• However, $C_T$ is strongly influenced by the cathodic polarization.

• Steel at adjacent sites cathodically polarized by the local anode provides local cathodic prevention ($C_{prev}$).
HALO EFFECT

- Passive, Cath. polarized -200 mV_{CSE}
- Active -400 mV_{CSE}
- Passive -100 mV_{CSE}

• As corrosion continues with time at local anode, concrete degradation occurs and need for repair is identified
• Corrosion damage at local anode repaired by removing chloride contaminated concrete. Removal of the anode from repairs disrupts local $C_{prev}$
• $C_{prev}$ is no longer afforded to sites adjacent to the former local anode.
Steel corrosion develops around the repair causing premature failure.

Phenomena partly explains why corrosion of steel adjacent to concrete patch repairs occurs in ‘halo’ effect.
ULTRA HIGH-PERFORMANCE CONCRETE (UHPC)

• UHPC becoming more common in bridge construction.
• UHPC has beneficial mechanical and material properties:
  • High $f'c$, $f't$, ductility, low permeability, and etc…

• Low permeability would indicate enhanced corrosion durability in bulk concrete.

✓ How effective is UHPC in mitigating corrosion in repair applications?

Corrosion testing of non-proprietary UHPC

- Corrosion of non-proprietary concrete mix designs examined by Floyd et al., 2020 at the University of Oklahoma.

- Rapid Chloride Permeability Test (ASTM C1202) on bulk concrete.

- Anodic Galvanostatic Polarization Test (0.2 A) on composite NSC-UHPC in 5% salt solution.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Cement (60%)</td>
<td>1,180 lb</td>
</tr>
<tr>
<td>Silica Fume (10%)</td>
<td>197 lb</td>
</tr>
<tr>
<td>Slag Cement (30%)</td>
<td>590 lb</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.20</td>
</tr>
<tr>
<td>Masonry Sand (1:1 ratio)</td>
<td>1,967 lb</td>
</tr>
<tr>
<td>Steel Fibers (2%)</td>
<td>265 lb</td>
</tr>
<tr>
<td>HRWRA (oz/cwt)</td>
<td>18 oz/cwt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>AA</th>
<th>Proprietary (2% fibers)</th>
<th>Non-Proprietary (2% fibers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapid Chloride (28 day)</td>
<td>2465 C</td>
<td>61 C</td>
<td>251 C</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>Negligible</td>
<td>Very Low</td>
</tr>
<tr>
<td>Rapid Chloride (56 day)</td>
<td>1832 C</td>
<td>28 C</td>
<td>63 C</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

- Non-proprietary UHPC demonstrated to have ‘Negligible’ to ‘Very Low’ chloride-ion permeability.

- Galvanostatic polarization to accelerate Cl⁻ ingress and corrosion rate.

✓ Corrosion developed in base concrete and sometimes in repair concrete and repair UHPC near joint.

Corrosion current from anodic galvanostatic polarization appeared to concentrate in base concrete near the composite concrete joint with the application of UHPC. Effect less in conventional concrete and non-proprietary concrete due to higher permeability (greater steel polarizability).

Recent research examined the corrosion durability properties of UHPC and the use of UHPC to mitigate macrocell corrosion caused by the presence of incipient anodes in concrete repairs with dissimilar concrete materials.

The objectives were to:
1) identify the possible beneficial properties of UHPC related to corrosion;
2) investigate if UHPC mitigates corrosion; and
3) identify the effect of the incipient chloride content.
METHODOLOGY

• Two test setup used.
  • Concrete cylinders (75%RH, 100%RH and soaked) for bulk resistivity and oxygen diffusion tests.
  • Concrete prisms for corrosion macrocell tests.
• Repair concrete UHPC and 0.48 w/c ratio conventional concrete.
• Substrate concrete 0.6 w/c ratio conventional concrete with chloride additions (0, 0.4%, 4%, and 8% Cl\textsuperscript{-} by cement weight).
• Electrochemical testing including 4-point resistivity, potentiodynamic polarization, and macrocell current.
• Macrocell tests examined the effect cathode-to-anode ratio. Anodic area assumed to be steel surface area in the substrate concrete and cathode area assumed to be in repair concrete.
In the conventional concrete, the bulk resistivity was differentiated by the external exposure moisture levels.

- External moisture levels did not affect the resolved bulk resistivity of the UHPC.

As expected, much larger bulk resistivity for UHPC compared to conventional concrete indicating lower permeability for UHPC.
OXYGEN DIFFUSIVITY

- Oxygen diffusivity ($D_{O2}$) calculated from fitted limiting current from potentiodynamic polarization tests.
- Lower oxygen diffusivity generally observed in concretes immersed in water.
- Lower cathodic and limiting current was measured for UHPC in all moisture exposure conditions compared to the 0.48 w/c conventional concrete.

Lower $D_{O2}$ for UHPC indicating reduced oxygen availability to support corrosion reduction reaction.

• Steel in chloride-rich substrate generally showed active potentials.
• Steel in chloride-free substrate showed passive conditions in dry concrete but some active potentials measured in NSC after wetting.
• Steel in chloride-free UHPC and NSC repair generally showed passive conditions.

Electrical resistance of NSC significantly dropped upon concrete wetting.
Electrical resistance of UHPC remained high after wetting.

Low macrocell currents were measured for both UHPC and NSC in the dry condition (0 and 0.4% wt Cl- in substrate concrete).

With higher Cl- levels, larger macrocell currents developed (and enhanced after wetting).

Lower currents when repair with UHPC even after wetting.

High resistivity of UHPC would minimize coupling between active steel and cathodes in repair concrete.
MACROCELL CURRENT BETWEEN REPAIR AND SUBSTRATE CONCRETE

- Low macrocell currents developed in samples with conventional and UHPC repair concrete when the vestigial chloride content in the substrate concrete was low.

At higher Cl- levels, larger cathode-to-anode ratio generally resulted in enhanced macrocell for both UHPC and NSC.

Effect of larger extended cathodes outside of repair concrete may further enhance macrocell. Additional work on larger geometries.

• Reinforced concrete T-Beam with UHPC overlay
• Portion of top flange remained NSC with and without chloride contamination
• OCP and macrocell current measured
• Macrocell with extended cathodes in UHPC overlay and rebar within substrate NSC concrete.

LARGE TEST GEOMETRY (REINFORCED CONCRETE WITH REPAIR UHPC)

- Rebar potential in chloride-contaminated NSC substrate indicative of corrosion initiation.
- Galvanic coupling of steel in adjacent NSC caused polarization of steel.
- Elevated cathodic rates in chloride-free NSC support elevated corrosion rates in anodic region.
- Steel within the UHPC overlay remained passive throughout the flange.
- Early macrocell currents still elevated with extended coupling to steel in UHPC.
- Less than coupling with steel in concrete core substrate.
- Less differentiation in macrocell by day 100.

- Patch and encapsulation repair create cold joints between dissimilar concretes.
- Surface roughness, cleanliness, and moisture levels can affect bond.
- Small scale lab experiments examined Cl⁻ penetration at cold joints with various preconditioning surface moisture levels.

**EFFECT OF REPAIR COLD JOINTS ON CHLORIDE PENETRATION**

• Splitting tensile test indicated enhanced tensile performance for UHPC (5x greater than NSC and composite specimens).
• Nevertheless, good bonding for composite specimens (>2,1 Mpa).
• Plain UHPC and NSC had highest and lowest charge passed, respectively.
• Composite specimens (except at 0%RH) showed intermediate values.
• Chloride penetration observed by silver nitrate spray.
• As expected, Cl⁻ penetration through joint was higher with presence of excess moisture (i.e., soaked condition).
• Non-uniform penetration sometimes observed at joint interface.
• Results did not show large effect of moisture conditioning as good bond was attained for all samples.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Cl⁻ Penetration Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% RH</td>
<td>8</td>
</tr>
<tr>
<td>75% RH</td>
<td>16</td>
</tr>
<tr>
<td>100% RH</td>
<td>5</td>
</tr>
<tr>
<td>SOAKED</td>
<td>76</td>
</tr>
</tbody>
</table>

DISCUSSION

• Macrocell current was much reduced in samples repaired with UHPC even with higher vestigial chloride presence in the substrate concrete however substrate concrete containing significant chloride content should be removed prior to application of any repair materials including UHPC.

• In practical application of repair concrete in marine concrete substructures, the placement and geometry of the repair patch can significantly affect the durability of the structural element. If the repair were to be localized, the beneficial attributes of the UHPC may also be localized.

• Characterizing chloride transport through the cold-joint interface between the substrate and repair concrete and the effect of mechanical stresses that may develop at the concrete interface due to corrosion propagation should be addressed.
CONCLUSIONS

- UHPC showed **bulk resistivity** up to an order of magnitude larger than the tested conventional concrete, consistent with its higher cement factor and relatively low internal moisture content due to **its low permeability**.

- The calculated approximate **oxygen diffusivity** for UHPC was much lower than the conventional concrete, and lower diffusivity was observed in UHPC exposed in immersed conditions than in ambient humidity conditions.

- Low macrocell currents developed in samples with conventional and UHPC repair concrete when the chloride content in the substrate concrete was low.

- Even though higher current was observed in wet condition compared to the dry condition, the increased current in samples repaired with UHPC was significantly lower than comparative testing with NSC.

- Macrocell current was enhanced at higher C/A for samples utilizing NSC and UHPC for the repair concrete.
Thank You!

Questions???